THE WORLD OF CHEMISTRY

Program #21

CARBON

Producer John Ketcham

Air Script: October 31, 1988

PRODUCED BY

EDUCATIONAL FILM CENTER
and
THE UNIVERSITY OF MARYLAND

THE WORLD OF CHEMISTRY

Program #21: Carbon
Producer John Ketcham
Air Script: October 31, 1988

Annenberg/CPB Project Logo and Music

Funder Credits

MONTAGE: Nature shots, assembly line machinery, grocery store, pills, plastics, paint, graphic, chemists at work in labs, fire

NARRATOR (MUSIC and NAT SOUND under):
The element essential for life is carbon. Plants and animals alike are made of carbon compounds. Why does nature find carbon so essential? The diversity of life reflects the complexity of carbon compounds. But there's more. Paints, pills, and plastics are all made from carbon compounds, too. So are glues and dyes. How can that be? How can one atom be so versatile? The largest and most organized branch of chemistry, organic chemistry, is devoted to unraveling the mysteries of carbon.

SUPER: CARBON

THE WORLD OF CHEMISTRY OPEN: Montage, Music, Logo

RH at chemical plant

ROALD HOFFMANN (SYNC):
Nearly every molecule in my body, or in this pine tree, or in a virus such as the AIDS virus, is made of carbon. There are other essential elements, oxygen, nitrogen, even iron. These add variety and function, but the underlying structure of biological molecules is built on the carbon atom. These carbon compounds can be simple, like acetic acid, or they can be complex, like the elegant giant oxygen carrier in our blood, hemoglobin. But in every living organism there are thousands of organic molecules. Chemists have made millions of carbon-containing molecules that have never existed on earth before. A natural question is, why carbon? Well, carbon forms four bonds readily to itself, to other elements. Other atoms also form four bonds, or even more, but those bonds are usually labile and weak. The bonds that carbon forms are strong, and they persist even in the presence of water and of oxygen. They allow carbon to build chains, rings, molecules of incredible complexity. They allow our bodies to function, these plants to work. Carbon is really unique.

MONTAGE: Nature shots, microorganisms, chemical plant shots, factory assembly lines, nylon

NARRATOR (MUSIC and NAT SOUND under):
Fall in the Blue Ridge Mountains. Winter's gone and summer's not far off. Our natural world is constantly changing. Every living thing which surrounds us, the plants and animals, from the smallest single organism to the enormous, all are based on one essential element, carbon. Some scientists suggest that life couldn't exist anywhere in the universe without carbon. Not far away, crude oil is being separated into many different compounds, and those, in turn, are being made into fuels, fabrics, and pharmaceuticals. Synthetic carbon-based products are everywhere. It's hard to imagine life without them. But nylon has only been around for 50 years.

Archival footage: nylon and nylon factory, chemists in labs, archival drawings of lab work, archival photograph of Wohler

NARRATOR (MUSIC under):
Nylon was quickly made into everything from parachutes to carpeting. Today we take organic synthesis for granted, but until the 19th Century, people believed that certain compounds could only be made by living things with divine intervention of a vital force. (cont.)

NARRATOR cont:
An unexpected experiment in a Heidelberg laboratory changed that belief. Friedrich Wohler, a well-known German scientist, set out to synthesize a salt, ammonium cyanate.

EQUATIONS

Though the solid he made had the same molecular formula, it was not a salt. Many experiments later, it was found to be urea, a covalent compound, a compound already isolated from human urine. Wohler had made an organic compound out of inorganic materials.

Chemists at work in labs, computer models

NARRATOR (NAT SOUND under):
Today, we can make simple carbon compounds or ones that are incredibly complex. How can carbon form such a variety of compounds? The secret lies in its ability to form strong covalent bonds with itself.

GRAPHIC: Carbon bonding

NARRATOR (MUSIC under):
Carbon is a relatively small atom, with four valence electrons with which it can form a variety of covalent bonds. If these bonds are all single bonds, the geometry of the molecule looks like this, a tetrahedron. (cont.)

NARRATOR cont:
Here each of the four carbon electrons bonds with one electron from a hydrogen atom to form methane, the major component in natural gas. Two carbon atoms can share a pair of electrons and form single bonds with each other, as in this molecule, ethane. Each carbon atom is bonded to three hydrogen atoms and to another carbon. It can form double bonds with itself. In this example, the four available bonds of each carbon include two single bonds with hydrogen atoms and a double bond with another carbon, where two pairs of electrons are shared. This is ethylene. Notice the geometry of the molecule has changed. Carbon can also form a triple bond with another carbon atom. It does this by sharing three pairs of electrons. Again, the geometry changes. This is acetylene, which is burned in welders' torches. Carbon-to-carbon bonds are fairly strong and are not easily broken. Carbon atoms can form compounds with long chains like this one, with 18 carbon atoms linked together. They can form rings, which can be simple, or complex.

MONTAGE: Race cars, oil and petroleum, butane lighters on assembly line

NARRATOR (MUSIC and NAT SOUND under):
We've been looking at compounds of carbon and hydrogen, hydrocarbons, which include most of the fuels we use, petroleum, gas, gasoline. All are mixtures of hydrocarbons. Analysis of these mixtures reveals an amazing variety of hydrocarbons. Some have the same molecular formulas, but different structures. These are isomers. The butane in these lighters is a good example.

GRAPHIC: Hydrocarbon isomers

NARRATOR (MUSIC under):
Butane is a simple hydrocarbon with 4 carbon atoms and 10 hydrogen atoms. The carbon atoms can form a simple chain, or there can be side chains, like this. Both of these compounds have the same molecular formula, C4H10, but they are two distinct compounds, butane and isobutane, and they have different properties. Here's another example, pentane. It has five carbon atoms, C5H12. We'll take away the hydrogen atom so we can concentrate on the carbon skeleton. The five carbon atoms can be arranged in three different ways, as a single chain, or a chain with one or two branches. (cont.)

NARRATOR cont:
Each of the three compounds are different. They have their own physical and chemical properties, but they have the same molecular formula, C5H12. Compounds that have the same formulas but different structures are called structural isomers. It gets complicated. The more carbon atoms in the molecules, the higher the number of possible isomers. The hydrocarbon with 8 carbons, octane, a major component of gasoline, has 18 possible isomers. A molecule with 20 carbons has over one-third of a million potential isomers.

MONTAGE: Hair spray, products on grocery store shelves, refrigerator, archival nylon footage, computer models

NARRATOR (MUSIC and NAT SOUND under):
Butane and isobutane are both in this hair spray, so are many other carbon compounds. While the number of combinations of hydrogen and carbon atoms seems endless, organic compounds do not only include carbon and hydrogen. Refrigerants contain halogens as well. Nylon has nitrogen and oxygen also in its structure. Combined with nitrogen, oxygen, sulfur, and phosphorous, we get even more varieties.

MONTAGE: Chemical plant shots, gas station, chemists at work in labs, assembly line shots, drinking soda pop

NARRATOR (MUSIC and NAT SOUND under):
How can we sort through this universe of carbon compounds? There is an organization to it. Organic compounds contain structures called functional groups, that have a predictable chemical behavior wherever they appear. They make ethyl alcohol here. Sugar cane and corn stalks are being digested by yeast and converted to ethyl alcohol. The hope is that someday gasoline will be replaced by a renewable fuel such as ethyl alcohol. The millions of organic compounds can be identified according to the nature and the number of the functional groups they contain. How?

EQUATIONS

Alcohols, and there are many, all have this OH bonded to a saturated carbon atom. This OH is known as the alcohol functional group. Another functional group characterizes acids. Citric acid and acetic acid are probably familiar to you. We know acetic acid as a dilute solution in water, vinegar.

EQUATION

Organic acids have this carboxyl functional group, in which a carbon atom forms a double bond with an oxygen atom, and a single bond to an OH group. (cont.)

NARRATOR cont:
If you react an alcohol, like ethyl alcohol, with an organic acid, like acetic acid,

EQUATIONS

another functional group is created, an ester. In this case, ethyl acetate. Esters have properties which are distinctly different from either alcohols or acids. Alcohols and acids are fairly common. But you're also acquainted with esters, because esters are used in the flavor and fragrance industry.

INTERVIEW: A. Allen Bednarczyk, V.P. Scientific Affairs, Quest International, shots of soda pop assembly lines

SUPER: A. Allen Bednarczyk, V.P. Scientific Affairs, Quest International

A. ALLEN BEDNARCZYK (VO/SYNC):
If a company wants to produce a carbonated beverage, that company will know how to carbonate the water, package it, distribute it, but they would come to a company like Quest International to provide the orange flavor, the cola flavor, grape flavor.

Shots of Quest International

NARRATOR (MUSIC and NAT SOUND under):
This is Quest International in Owings Mills, Maryland. They make flavors here -- orange, grape, raspberry, banana. At Quest they're looking for that something extra.

Shots of Quest International

A. ALLEN BEDNARCZYK (VO):
To make a flavor, the first thing we have to do is find out what Mother Nature did in her particular food to give us the flavor of a banana or a strawberry or raspberry.

Shots of Quest International

NARRATOR (MUSIC under):
The Quest chemists analyze natural flavors, the chemistry of a banana, and then they try to duplicate it in the lab.

INTERVIEW: A. Allen Bednarczyk cont.

A. ALLEN BEDNARCZYK (SYNC):
You can mix together 20 or 30 chemicals, smell them and it smells like a peach or strawberry, and it's seen nothing but a test tube. This is terrific.

Archival footage of perfume smelling, archival photographs of lab work, fragrance testing

NARRATOR (MUSIC under):
Using esters in the flavor industry isn't new, but in the hundred years or so that chemists have been duplicating nature's flavors and inventing new ones, business has grown. Quest supplies flavors to about 200 of the world's most well-known food companies. But esters are used to do more than flavor soda pop and candy. One of the world's most secretive industries uses esters, too, to add fragrance to perfumes. Chemists can mix up new smells, but it's up to the best-trained noses to pass them or fail them. There is a limit to human tolerance of new smells and tastes.

Shots of testing and tasting new flavors

A. ALLEN BEDNARCZYK (VO):
We're not going to start mixing together chemicals and saying, "Here, taste this," because if the public can't relate to that flavor, if it's not a flavor that they're familiar with, after generations and generations, they're going to reject it.

RH at chemical plant

ROALD HOFFMANN (SYNC):
It's interesting to analyze organic molecules to find out what atoms are there, to see how the carbon chain is connected up. (cont.)

ROALD HOFFMANN cont:
It's even more fun to make them in the laboratory, to use those functional groups as logical building blocks to assemble complex molecules. Some of the things that we make in that way will be similar to what there is in nature already, and some of the molecules will be entirely new. The making of molecules is called synthesis. Synthesis can be done as a game. It can be done as an intellectual exercise. Think, for instance, of the challenge of plotting the strategy to make a molecule as complex as DNA. Synthesis is also potentially valuable and profitable.

MONTAGE: Aspirin on assembly lines, stone sculpture of Hippocrates, willow trees, archival photographs of Bayer Company and chemists in the lab

NARRATOR (MUSIC under):
Over 2,000 years ago, Hippocrates recommended chewing willow bark to relieve pain. It worked. By the mid-1800s, it was known that the active ingredient was salicylic acid. But willow bark was bitter medicine. It wasn't until 1899 that the German Bayer Company began the industrial conversion of salicylic acid to acetylsalicylic acid. This was easier to take. (cont.)

NARRATOR cont:
Today, nearly 36 billion aspirin are used every year in the United States alone. That's a lot of headache relief. Aspirin has two functional groups, an acid and an ester. How is it made?

DS in lab

DON SHOWALTER (SYNC):
Now, I have a little salicylic acid here on this paper. I am going to introduce it into this test tube. I weighed out 138 milligrams of salicylic acid. Let's see if I can transfer it all into this small test tube. Good, it's all in there. All right. Next thing I must add is one drop of phosphoric acid. That's used as a catalyst, to speed up the reaction, huh? And then the other active ingredient now, the major reactant, is acetic anhydride. I need to add point 3 milliliters of that. If we remember, in the laboratory many times we will uses the measurement of 20 drops per milliliter. So that means I should add six drops for point 3 milliliters. Five and six. And we'll shake it up a little bit and mix up all the reactants. And then we need to heat it for five minutes at 90 degrees. I have a little water bath here, and let me check the temperature. It looks good, it's right in that region. And we'll put it in there and heat it now for about five minutes. (cont.)

DON SHOWALTER cont:
Well, it looks like our have five minutes is about up. We'll take the test tube out of there with our mixture, and I want to add some cool water to that. Now the water will react with the excess acetic anhydride, forming acetic acid. All right, a little bit more. All right. Now we'll let it cool. And as the mixture now cools, we should see crystals form of acetylsalicylic acid, aspirin. What I have to do, it has to get cooler -- oh, here it goes now. Look at that. See that cloudiness now turning into a more and more dense mixture now so the aspirin is precipitating out of there. Okay. Let's see if we can filter it now and see if we can recover any product, huh? So I'll turn on this suction over here. I have a suction setup, suction filtration. And let's see if we got any aspirin out of there, huh? What we can do is turn off that suction, and I'll lift up that filter paper, see what we've got. Oh, look at that. Now there's the aspirin we made. Let's see if we can scrape it onto here so I can get a good look at that. That's acetylsalicylic acid. Well, we did it, but I'm sure glad I don't have a headache now, because we have just made about one-third of the acetylsalicylic acid that is in one aspirin tablet.

Aspirin on assembly line, plant roots

NARRATOR (MUSIC and NAT SOUND under):
The billion-dollar aspirin industry began with willow bark. Chemists were able to isolate and then improve on the naturally occurring pain reliever, salicylic acid. Are there other natural wonder drugs? The use of plants in folk medicine has a long history. Dr. Kathlyn Parker.

INTERVIEW: Dr. Kathlyn Parker, Brown University

SUPER: Kathlyn Parker, Brown University

DR. KATHLYN PARKER (SYNC/VO):
There's a really long history of folk medicine based on plants, especially actually in the Near East and the Far East, in China.

Making folk medicines

Now the question is which of these things really works and how much of it is just a rumor or is it really true?

NARRATOR (MUSIC under):
Scenes like this have been repeated in India for thousands of years, and Dr. Parker has found there's some truth to folk medicine.

DR. KATHLYN PARKER (SYNC/VO): First of all, you check out the plant which is rumored to be good, and check its extracts to see if there's any activity there.

INTERVIEW: Dr. Kathlyn Parker cont.

This molecule is called frederickamyacin. Frederickamyacin is an antibiotic which is of some interest as a possible anti-tumor compound. This comes from a soil organism, a bacterium which is found in the soil in Frederick, Maryland, which is right around the corner.

Chemist working in lab

NARRATOR (NAT SOUND under): What Dr. Parker and other researchers do is, first, analyze the substance in the lab. If they find an active part of the molecule, they look further.

INTERVIEW: Dr. Kathlyn Parker cont.

DR. KATHLYN PARKER (SYNC/VO): Then, if you are really interested in drug development, you have to isolate the active component, purify it, determine its structure, and then it gets handed over to the pharmaceutical people who decide how to package it.

Drugs and medicine bottles on assembly lines

DR. KATHLYN PARKER cont:
For some pharmaceuticals, what you really need is to be able to make a large amount of stuff really cheap. One solution is that you would develop methods so that it was so cheap to make something that you could distribute it to people in a way that they could afford it.

Third World footage, chemists at work in labs, assembly line, aspirin on shelf

NARRATOR (MUSIC and NAT SOUND under):
The need for inexpensive and effective medicine is crucial in developing countries. The population that would directly benefit would be children. How is small-scale laboratory synthesis converted into economic industrial synthesis? Where do raw materials come from? Are the challenges of the laboratory very different from those of mass production? Once the salicylic acid was isolated from willow bark and then converted in the laboratory, how was aspirin mass-produced? It all starts with benzene. But what chemical trail leads to aspirin on the drugstore shelf?

GRAPHIC: Simplified reaction pathways to aspirin, and from benzene

NARRATOR:
Aspirin, as we saw, was made from salicylic acid. The salicylic acid was made by treating phenol with carbon dioxide and sodium hydroxide. Phenol comes from cumin hydroperoxide, which is made from cumin, which is derived from benzene, and benzene is used to manufacture many products, not only aspirin, but polystyrene, and plastics, dyes and drugs, detergents and glue -- they're all molecules derived from benzene.

Petroleum plant shots

NARRATOR (MUSIC and NAT SOUND under):
We produce about five million tons of benzene every year for America's chemical industry. Most of it comes from petroleum, and each of the benzene derivatives can be manufactured at different locations and then shipped to other factories by pipeline or train. America's chemical industry is connected by a vast network which supports the eventual production of millions of products. Dr. Mary Good, President of Engineered Materials Research, Allied Signal Corporation.

INTERVIEW: Dr. Mary Good, President of Engineered Materials Research, Allied Signal Corporation

SUPER: Mary Good, Allied Signal Corp.

DR. MARY GOOD (SYNC/VO):
You really have a huge network from the raw materials which are primarily petroleum to the refinery situation, which is primarily the place in which you get starting materials. And those starting materials are then used to make petrochemicals. The petrochemicals then are used to make all kinds of things, from plastics to medicines, drugs to whatever.

Chemical plant shots

I would guess that if you looked at it, probably 25 to 40 percent of the population of the country, in one way or another, is probably dependent upon that infrastructure.

NARRATOR (MUSIC under):
One of the reasons for the size of that chemical network is the number and variety of products produced by it. Another reason: the chemical industry, like all industries, makes its money on volume.

INTERVIEW: Dr. Mary Good cont.

DR. MARY GOOD (SYNC):
These are not high margin kinds of things, normally. So you can't afford to make mistakes and you can't afford to have waste. It's not in anybody's economic interest to have them.

Chemical plant shots

NARRATOR (MUSIC under):
Due to the size of he industry, mistakes can happen, and inefficient chemical processing can produce waste.

DR. MARY GOOD (VO/SYNC):
You're gonna see a lot of work, I think, on, on redesigning chemical processes to make -- to reduce waste. In other words, just not to have it reformed if possible. You're gonna have a -- see a lot of effort in recycling.

INTERVIEW: Dr. Mary Good cont.

If people could have some understanding of the volume of chemicals that are made in the United States every day, if you could then put in perspective the very small number of incidents that happen, one would have a better feeling for what the risk-benefit kinds of ratios are.

SUPER: CARBON

MONTAGE: Nature shots, program graphics, chemical plant shots, aspirin, nylon, factory shots

NARRATOR (MUSIC under):
To review: All living things are primarily made of carbon compounds. Natural variety, and the seemingly unending development of new organic compounds is possible, in part because of the versatility of carbon in forming covalent bonds. It can form single, double, or triple bonds with itself and other elements. Structural isomers have the same molecular formula, but the atoms in the carbon skeleton are arranged differently. Each isomer has distinct properties. Handling this huge number of substances would be impossible if it were not for the existence of functional groups. Compounds like benzene are the source of a host of other useful substances. The challenges posed by synthesis change as production moves from the laboratory to the factory. Factors that must be considered are cost and availability of raw materials, and the ability to reduce and dispose of the waste.

RH at chemical plant

ROALD HOFFMANN (SYNC):
The chemistry of carbon, organic chemistry, is at the same time the most logical and the most highly developed part of our science. The logic you've seen in isomers and in functional groups. And you've gotten the hint of the complexity, for instance, in that marvelous structure of frederickamyacin that Dr. Parker discussed, or in the industrial synthesis of aspirin? You know, science is a curious mixture of discovery and creation. Discovery I take in the sense of revealing or uncovering some perhaps hidden laws of nature. Creation is, of course, the making of things. Now, if you ask scientists what they do, they tend to stress discovery. But artists, writers, painters, musicians, would tend to emphasize just the opposite, creation. Artists might reveal the essence of nature or of some emotion, but the fundamental achievement of the artist is the creation of a new reality. Well, the making of molecules brings chemistry pretty close to the arts. For what we do is we create, with our hands, with our minds, the objects, molecules, of our own study and appreciation. (cont.)

ROALD HOFFMANN cont:
The synthesis of molecules, be it of aspirin, of an antitumor agent, of nylon made here at Du Pont by Wallace Caruthers 50 years ago, the synthesis both plan and design is an artistic achievement of the highest order.

Credits, Closing Montage, Closing Music

Copyright © 1988
Educational Film Center
and The
University of Maryland

The World of Chemistry Logo

A Production of
UNIVERSITY OF MARYLAND
AND
EDUCATIONAL FILM CENTER

The Annenberg/CPB Project Logo

Funder Credits

1-800-LEARNER

PBS Logo